RELATION OF MACROINVERTEBRATE COMMUNITY IMPAIRMENT TO CATCHMENT CHARACTERISTICS IN NEW JERSEY STREAMS[1]

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ABSTRACT: The level of macroinvertebrate community impairment was statistically related to selected basin and water-quality characteristics in New Jersey streams. More than 700 ambient biomonitoring stations were chosen to evaluate potential and known anthropogenic effects. Macroinvertebrate communities were assessed with a modified rapid-bioassessment approach using three impairment ratings (nonimpaired, moderately impaired, and severely impaired). Maximum-likelihood multiple logistic-regression analysis was used to develop equations defining the probability of community impairment above predetermined impairment levels. Seven of the original 140 explanatory variables were highly related to the level of community impairment. Explanatory variables found to be most useful for predicting severe macroinvertebrate community impairment were the amount of urban land and total flow of municipal effluent. Area underlain by the Reading Prong physiographic region and amount of forested land were inversely related to severe impairment. Nonparametric analysis of variance on rank-transformed bioassessment scores was used to evaluate differences in level of impairment among physiographic regions and major drainage areas simultaneously. Rejection of the null hypothesis indicated that the levels of impairment among all six physiographic regions and five major drainage areas were not equal. Physiographic regions located in the less urbanized northwest portion of New Jersey were not significantly different from each other and had the lowest occurrence of severely impaired macroinvertebrate communities. Physiographic regions containing urban centers had a higher probability of exhibiting a severely impaired macroinvertebrate community. Analysis of major drainage areas indicates that levels of impairment in the Atlantic Coastal Rivers drainage area differed significantly from those in the Lower Delaware River drainage area.
(KEY TERMS: aquatic ecosystems; bioassessment; macroinvertebrates; water quality; land use; urbanization; modeling/statistics.)

INTRODUCTION

The U. S. Geological Survey (USGS), in cooperation with the New Jersey Department of Environmental Protection (NJDEP), established a statewide surface-water-quality monitoring network in the early 1970s that currently provides the basis for the State water-quality inventory report to the U.S. Environmental Protection Agency (USEPA) and Congress mandated by section 305(b) of the Federal Clean Water Act (N.J. Department of Environmental Protection, 1992). This cooperative network has been useful in providing data to describe trends in nutrients, major ions, and other water-quality characteristics in New Jersey streams (Hay and Campbell, 1990; Price and Schaefer, 1995; Robinson et al., 1996; Smith et al., 1993). Concurrently, a biomonitoring program incorporating a regional reference network was developed cooperatively by the NJDEP and USEPA to provide a solid biological foundation for statewide water-quality planning and management decisions involving surface water quality standards and biocriteria (N.J. Department of Environmental Protection, 1994c).

The USGS began full implementation of the National Water Quality Assessment (NAWQA) program in 1991 to address similar issues at a national scale. NAWQA is a long-term program designed to provide a nationally consistent description of the current status of and trends in the quality of the Nation's surface- and ground-water resources and to provide an understanding of environmental factors that affect the quality of these resources (Leahy et al., 1990). The NAWQA program is organized into 59 hydrologic basins (study units) across the country that differ widely with respect to the natural and human factors that affect water quality (Gilliom et al., 1995). Work in the Long Island-New Jersey study unit began in 1994, and although this study unit is one of the

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smallest in the NAWQA program (15,540 km²), it includes some of the most heavily urbanized and densely populated areas in the Nation.

One goal of the NAWQA program is to evaluate physical, chemical, and biological factors that affect aquatic communities (Gurtz, 1994). This evaluation is typically accomplished through (1) analysis of available data and (2) intensive sampling of water chemistry and biological communities within each study unit. This paper addresses the first of these evaluations for the Long Island-New Jersey study unit. Two complementary studies were also conducted in which the presence and distribution of trace elements (O'Brien, 1997) and chlorinated organic compounds (Stackelberg, 1997) in bed sediments were evaluated.

In the past, the integration of biological and water-quality data on a drainage basin or larger scale has been hindered by the lack of consistent data, the small number or sites for which both types of data were available, and the high cost of simultaneously collecting a comprehensive suite of biological and water-quality data. Additionally, levels of community impairment commonly reflect a variety of indirect anthropogenic effects (e.g., nonpoint-source contamination) that can be difficult to quantify. Decisions regarding levels of acceptable deviation from baseline conditions established from comparisons to benchmark-type communities are more likely to be effective, however, if they are based on probability rather than on a subjective determination (Resh et al., 1995). Therefore, it is essential that levels of macroinvertebrate community impairment be related to basin and water-quality characteristics by using statistical tests of significance. Two approaches (multimetric and multivariate) frequently have been used independently to evaluate water-quality characteristics and community attributes (Reynoldson et al., 1997), however, there are few examples that integrate the two approaches. Additionally, the effectiveness and applicability of multimetric versus multivariate approaches has resulted in significant debate (e.g., Barbour and Gerritsen, 1996; Courtemanch, 1996; Norris, 1995; Reynoldson et al., 1997; Vinson and Hawkins, 1996).

The multimetric-based rapid-bioassessment approaches by Karr (1981), Hilsenhoff (1988), and Plafkin et al. (1989) have provided State and local agencies with a cost-effective framework for assessing stream condition (Hannaford and Resh, 1995; Resh and Jackson, 1993; Resh, 1994). The need to integrate multiple lines of evidence into water-quality assessments, identify problems associated with point- and nonpoint-source contamination, document long-term regional changes in water quality (Resh and Jackson, 1993), and supplement statewide water-quality inventory reports (Section 305(b) of the Federal Clean Water Act) has led to a proliferation of such approaches. Rapid-bioassessment approaches were first developed by using fish (i.e., Karr, 1981); however, benthic macroinvertebrates are currently the most widely used aquatic organisms for assessing water-quality conditions (Lenat and Barbour, 1994; Southerland and Stribling, 1995). Rapid bioassessments are typically based on a multimetric approach – that is an approach that uses an array of individual measures (community, population, and functional) to summarize diverse biological attributes into a single measure of biological condition that can be used to evaluate human effects on streams. The assessment of habitat quality has long been recognized as an important factor in the interpretation of biological data and is included in most rapid-bioassessments methods. Plafkin et al. (1989) provide three approaches for rapid bioassessment of macroinvertebrates, modifications of which already have been implemented in water-resource management by more than 20 states in the United States (Hannaford and Resh, 1995; Southerland and Stribling, 1995), including New Jersey (Kurtenbach, 1994; N.J. Department of Environmental Protection, 1994a). The categorical impairment ratings derived from multimetric approaches, however, does present the investigator with some analytical challenges.

Multivariate approaches have been shown to be powerful methods in ecological assessments (Zamora-Munoz and Alba-Tercedor, 1996) and, in contrast to multimetric procedures, are typically used to produce a predictive model derived from taxonomic composition (e.g., Reynoldson et al., 1995; Wright, 1995). The advantages of multivariate techniques are greater precision and accuracy (Reynoldson et al., 1997) and a reduction in the dimensionality of the data with minimal loss of information (Gauch, 1982). Unfortunately, data sets covering a large range of selected environmental gradients are uncommon because time, effort, and money required to adequately sample biological communities and a comprehensive suite of related environmental characteristics are great. This is especially true at the State level where budgetary constraints often limit sampling efforts.

Although the debate concerning the application and underlying philosophy of multimetric and multivariate approaches continues (Reynoldson et al., 1997), a need still exists to relate water-quality and basin characteristics to measures of biological condition derived from rapid bioassessments, and to examine the sensitivity of these conditions at the basin and state scales. The intent of this paper is not to deliberate further the applicability of multivariate or multimetric techniques, but to explore a non-linear predictive multivariate modeling approach designed

specifically to make maximal use of categorical data derived from multimetric-based rapid-bioassessments. The primary objectives of this paper are to (1) assess broad-scale differences in macroinvertebrate community impairment among major strata (drainage areas and physiographic regions), (2) relate levels of aquatic community impairment based on New Jersey's RBP to selected basin and water-quality characteristics, and (3) present an analytical approach using categorical data that is sensitive to differences in levels of community impairment. The results of this analysis will aid in the design of future biomonitoring efforts by surface-water managers, identify minimally disturbed systems that could benefit from protection, and pinpoint regions of New Jersey where concerted remediation efforts would be most effective.

STUDY AREA

New Jersey is composed of four primary physiographic provinces. From the northwest to southeast these are the Valley and Ridge, New England, Piedmont, and Coastal Plain provinces (Figure 1a). Underlying geologic formations within each province, except for the Coastal Plain, is similar in age, type, and composition. The area occupied by each province increases to the southeast. The Valley and Ridge province occupies the smallest area in New Jersey and is characterized by a series of parallel ridges and valleys trending northeast-southwest (O'Brien, 1997). The steep, mountainous topography of this region has deterred the intensive urbanization seen in most other regions of New Jersey. In general, much of the land is still large tracts of undeveloped forest and parks with some private woodlots and pastures. Elevation ranges from 120 m in the valley to more than 480 m along steep escarpments in the mountains. To the southeast, the New England province can be subdivided into New Jersey/New York Highlands (glaciated) and Reading Prong (unglaciated) subsections on the basis of the extent of the last Wisconsin ice sheet, which covered the northern part of New Jersey between 18,000 and 80,000 years ago (Figure 1b). This province consists of broad, flat-topped highlands and long, narrow valleys which range in elevation from 150-460 m. Southeast of the New England province is the Piedmont province, which is divided along the Wisconsin glacial moraine into the New Jersey/New York Piedmont and the Northern Piedmont Lowlands. Northwestward-dipping sedimentary rocks form broad, gently sloping lowlands and rolling valleys where elevations typically reach only 120 m.

Approximately 55 percent of New Jersey's area lies in the Coastal Plain (11,655 km^2). The Coastal Plain is separated from the northern physiographic provinces by the Fall Line (Figure 1a). The geologic, hydrologic, and topographic characteristics of the Coastal Plain are notably different from those of the northern provinces (Robinson et al., 1996). The Coastal Plain is underlain by layers of unconsolidated marine and fluvial deposits of sands, silts, clays, and fine gravels that dip gently to the southeast (Wolfe, 1977). Elevation generally ranges from 3 to 30 m along the broad river valleys. Some scattered hills reach elevations of up to 95 m.

METHODS AND APPROACH

Sampling Network

In the present study, data of more than 700 benthic macroinvertebrate samples collected as part of the NJDEP Ambient Biomonitoring Network (AMNET) program during 1992-96 were compiled (e.g., N.J. Department of Environmental Protection, 1994a,b). AMNET is an established network of lotic sampling sites located in major drainage basins in New Jersey (Figure 2). The goal of the program is to monitor benthic macroinvertebrate communities in each of the major basins on a five-year rotational basis. Sampling frequency was designed to represent a realistic temporal lag for assessing long-term environmental perturbations or recovery of sites resulting from water-quality improvements. Sampling locations were chosen on the basis of stream order, with at least one sampling site located on every first- and second-order stream 4.8 km or more long shown on USGS 1:24,000-scale topographic maps. Stream order is defined here as a measure of the position of a stream in a hierarchy of tributaries as described by Strahler (1957). This network also was designed to incorporate, wherever possible, existing USGS and NJDEP cooperative water quality monitoring stations to maximize integration of water-quality and biological information. Additionally, stations were chosen for monitoring mainstem locations above major confluences, assessing the effects of lakes, investigating known sources of contamination, and evaluating the effects of significant natural features such as wetlands, preserves, and wildlife-management areas. All sites were located topographically with a Global Positioning System (GPS).

EXPLANATION
NEW JERSEY
PHYSIOGRAPHIC REGIONS

Valley and Ridge (VR)
New Jersey/New York Highlands (NH)
New Jersey/New York Piedmont (PD)
Northern Piedmont Lowlands (PL)
Reading Prong (RP)
Inner Coastal Plain (ICP)
Outer Coastal Plain (OCP)

Figure 1b. Location of Physiographic Regions in New Jersey.

EXPLANATION
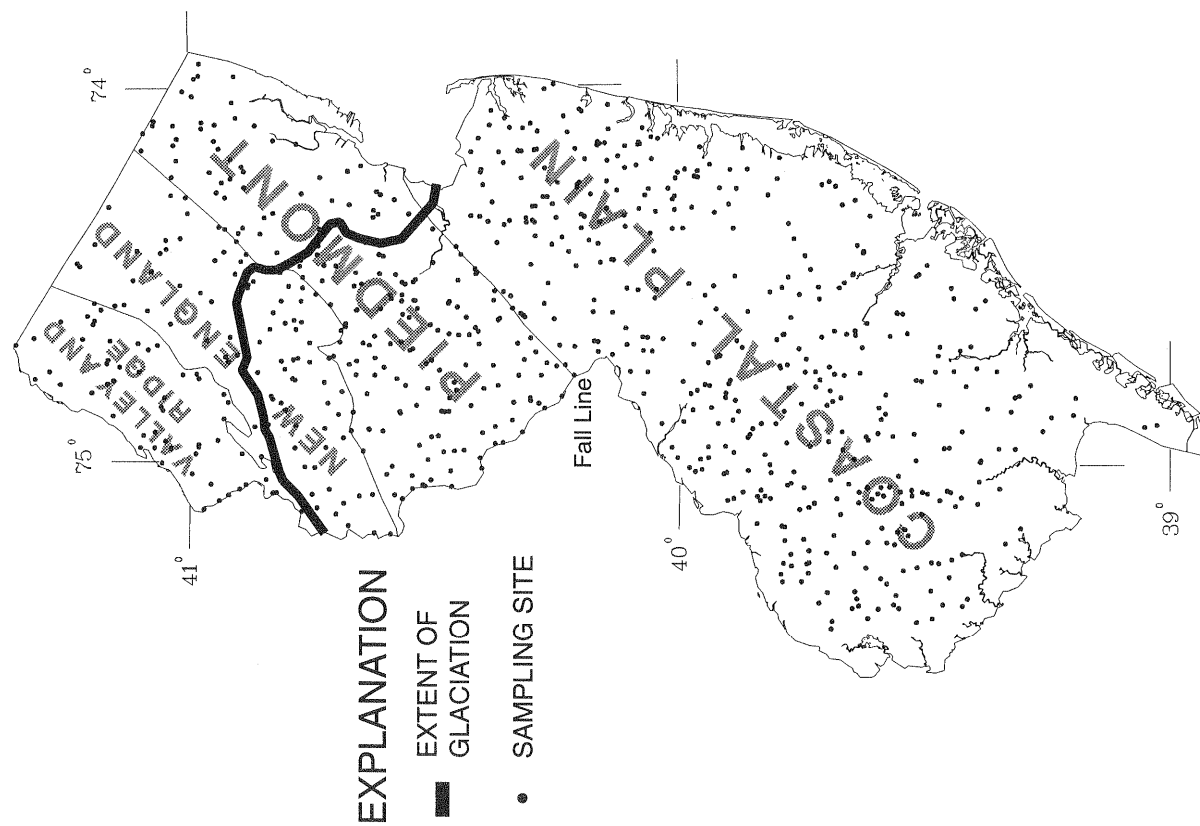
EXTENT OF
GLACIATION

• SAMPLING SITE

Figure 1a. Location of Ambient Biomonitoring Network Macroinvertebrate Sampling Sites,
Physiographic Provinces, and Extent of Wisconsin Terminal Moraine in New Jersey.
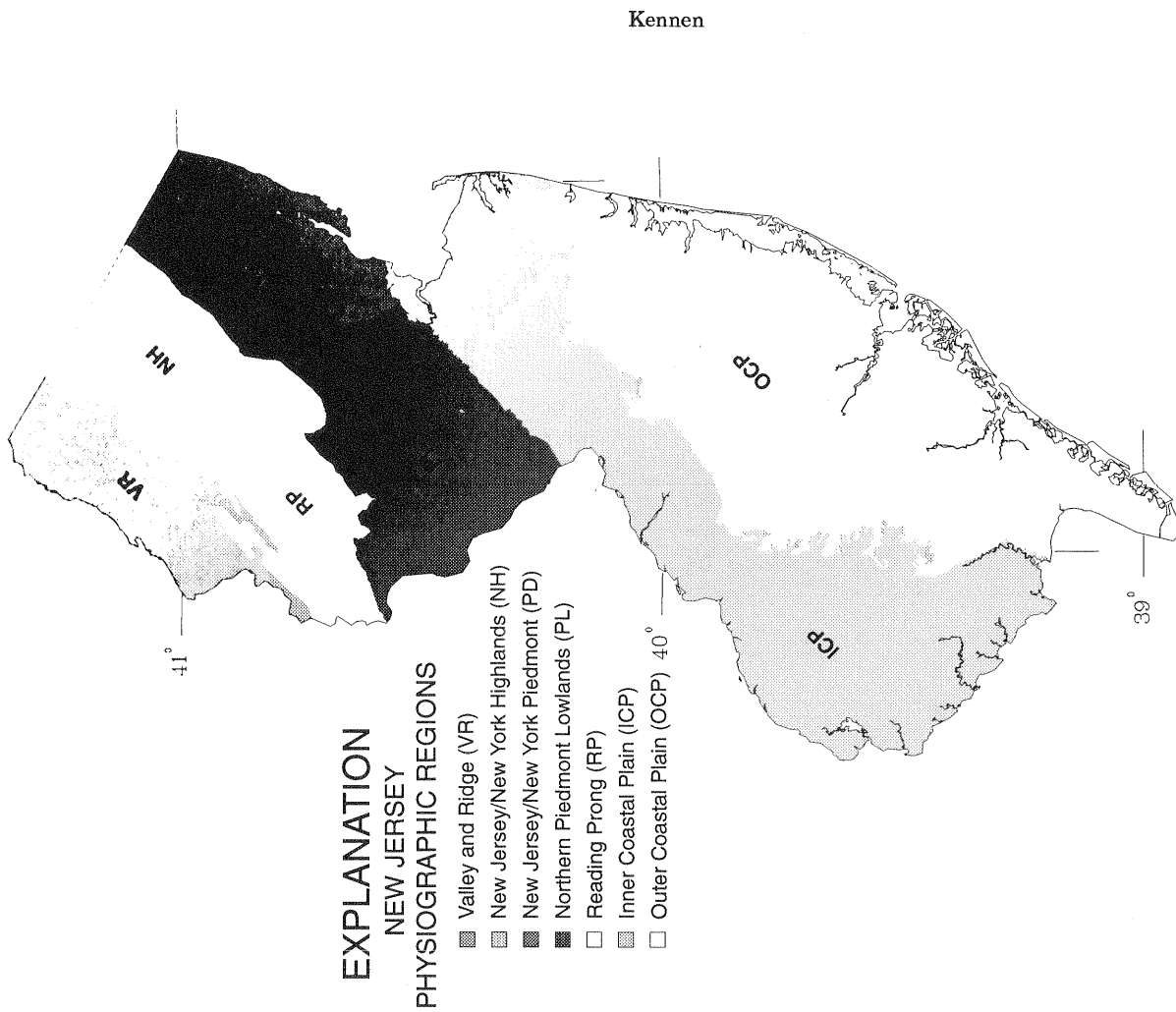
Macroinvertebrate Community Bioassessment

A rapid-bioassessment method for assessing regional differences in benthic macroinvertebrate communities was developed and field-tested for New Jersey streams (Kurtenbach, 1994). This approach is a modification of the USEPA's family-level rapid-bioassessment protocol (RBP II, Plafkin *et al.*, 1989). To validate the metrics used in the New Jersey's bioassessment approach, regression analysis was used to assess relations between biological condition and an independent measure of water quality (unpublished data on file at U.S. Environmental Protection Agency office in Edison, New Jersey). The water-quality index used in this assessment was devised to show the composite influence of eight constituents (temperature, oxygen, pH, bacteria, nutrients, suspended solids, ammonia, and metals) considered most important in determining water quality in New Jersey streams (N.J. Department of Environmental Protection, 1992). In addition, data collected from regional reference streams (N.J. Department of Environmental Protection, 1994c) provided a basis for comparing sites with macroinvertebrate communities displaying high biological integrity. Regional reference sites are minimally disturbed areas organized by selected chemical, physical and biological characteristics (Reynoldson *et al.* 1997) that were chosen to represent the full range of stream types in New Jersey. In high-quality streams, macroinvertebrate communities have structural and functional characteristics similar to communities found in regional reference streams. Communities of this type commonly exhibit high taxa richness, intolerance, abundance, and taxonomic equitability. Scoring criteria for the New Jersey rapid bioassessment approach was based on percent similarity to regional reference sites. Each metric was assigned a score according to the comparability of calculated and reference values. Scores for the metrics are totaled and compared to the total metric score of an established regional reference station (Plafkin *et al.*, 1989) that was determined a priori for physiographic regions in New Jersey (N.J. Department of Environmental Protection, 1994c). The resulting index was used to provide a cost-effective and reliable tool for assessing water-quality impairment in New Jersey streams.

Of the eight metrics comprising the USEPA's rapid bioassessment protocol (Plafkin *et al.*, 1989), four were retained (total taxa richness, total EPT richness, percent dominance, and family biotic index). One additional metric (percent EPT) not presented in the original USEPA protocol was included for use in the New Jersey RBP. The primary requirements for inclusion of metrics in the New Jersey RBP were low variability, the demonstrated ability to discriminate nonimpaired from impaired conditions, and statistical independence (non-redundancy). Many ratio and functional feeding group-based metrics were evaluated for inclusion (e.g., EPT/Chironomidae, scrapers/filterers, and shredders/total number of individuals), however, most were later excluded because of excessive variability and poor discriminatory ability. Functional feeding group indices used in RBPs are based on the assumption that ratios of organisms with different feeding strategies will change with environmental degradation (Norris and Georges, 1993). This is not always the case and it is sometimes difficult to assign taxa to appropriate feeding strategies. Additionally, Resh and Jackson (1993) found that most functional feeding group indices were not statistically capable of distinguishing between impaired and unimpaired conditions. Therefore, functional feeding group indices were not used in the present study. Sensitivity of metrics to impairment was assessed in the present study using standard t-tests and redundancy was evaluated using Pearson product correlation analysis (SAS Institute, Inc., 1990).

A brief description of metrics that met the criteria for inclusion in the New Jersey RBP is provided. (1) Total Family Taxa Richness – Measures the total number of families identified in the sample. A reduction in richness may indicate environmental stress related to organic enrichment, toxics, and sedimentation. (2) EPT Richness – Measures the total number of ephemeropteran, plecopteran, and trichopteran families in a sample. These organisms are considered to be highly sensitive to disturbance and typically the number of families vary inversely with the magnitude of environmental disturbance. (3) Percent Dominance – Assesses the relative balance within a macroinvertebrate community. Healthy macroinvertebrate communities often are characterized by an equitable faunal assemblage. Degraded streams commonly are dominated by a few highly tolerant taxa or taxa groups. (4) Biotic Index – Was developed to evaluate the relative tolerance of benthic macroinvertebrates to organic enrichment (Hilsenhoff, 1988). This index is based on a gradient or continuum that ranges from 0 (sensitive) to 10 (tolerant) and typically increases as water quality decreases (Plafkin *et al.*, 1989). (5) Percent EPT – Provides a measure of the percent abundance of three sensitive aquatic insect families. A high percentage of Ephemeroptera, Plecoptera, and Trichoptera in a sample is associated with good water-quality. Percent abundance of these groups often decreases with only minimal increases in environmental degradation. Although some redundancy appears to occur between metrics 2 and 5, these two biometrics were evaluated by Kurtenbach (1994) and found to be statistically independent.

Benthic macroinvertebrate samples were collected during the summers of 1992-1996, during stable-flow periods. The primary objective of the New Jersey RBP is to obtain a representative macroinvertebrate sample for each site within the limitation of time and money required for sorting and identification. To maintain consistency among sites, a random sampling design integrating areas of similar substrate composition, current velocity, water depth, and canopy cover was chosen (e.g., Kurtenbach, 1994). Cobble/riffle sections of the stream were the targeted habitat in northern New Jersey streams. Three replicate benthic macroinvertebrates samples were taken with a Surber sampler or a rectangular kick net (500-μm mesh) in cobble-riffle sections of the stream channel. The sampler was placed on the stream bottom and the substrate (approximately a 0.1 m^2 area) was vigorously disturbed to dislodge aquatic organisms, which were swept by the current into the trailing net (Bode et al., 1996). In low-gradient streams (conditions typical of streams located in southern New Jersey) organisms commonly attached to stream woody debris (sticks, snags, and logs) were targeted. Similar to the kick net procedure employed in the riffle areas, the sampler was placed downstream of the targeted habitat and the material was vigorously brushed, rubbed, or agitated to facilitate dislodgment of organisms. Depositional areas containing coarse particulate organic matter (twigs, leafs and pine needles), aquatic vascular plants, and sand-gravel bottom sediment were sampled using a grab sampler (Kurtenbach, 1994). All material from the targeted habitats and depositional areas was composited. Large organic and inorganic debris was inspected, rinsed, and removed. The remaining material was placed into a 1 L container and preserved with 10-percent formalin.

In the laboratory, samples were rinsed with tap water in a U.S. standard 30 sieve (500 mm) to remove fine sediments and excess preservative. Course organic debris was removed by flotation and sieving. The sample was placed on a white gridded pan and distributed homogeneously throughout the pan. Gridded sections of the pan (5.1 X 5.1 cm) were randomly chosen and a 100-organism subsample was systematically removed, sorted into taxonomic groups (usually order), and placed in vials containing 75 percent ethanol. This approach was based on the family-level protocols of Hilsenhoff (1988) and Plafkin et al. (1989). Macroinvertebrates were later identified with a 7-30x stereoscopic microscope. Chironomid larvae, oligochaetes, and other small aquatic fauna were typically slide-mounted and examined with a compound microscope under 40-400x magnification. All macroinvertebrates were identified by using applicable taxonomic keys (e.g., Brinkhurst, 1986; Pennak, 1989; Stewart and Stark, 1988; Wiggins, 1996). Specimens not readily identifiable were sent to specialists or scientists at other agencies for validation.

Regional Stratification

Many Federal, State and regional agencies stratify biomonitoring networks on the basis of relatively homogeneous units (e.g., physiography, ecoregions) which are largely predefined by geology, soils, climate, and vegetation (Omernik, 1987, 1995), or by major river systems that commonly cross physiographic, state, and political boundaries. To maintain consistency with previously established strata in New Jersey, the level of invertebrate community condition was examined with respect to physiographic regions and major drainages areas. These analyses were intended to demonstrate potentially broad-scale differences in level of invertebrate community impairment among the six major physiographic regions and major drainage areas (Figures 1 and 2). In this analysis, the New England and Piedmont provinces were analyzed on the basis of the glacial and nonglacial subsections previously described. Physiographic region designations are provided in Table 1a.

Because stream networks are not restricted by physiographic or political boundaries, environmental perturbations resulting form changes in land use and population density may vary among drainage areas. To assess these differences, five major drainage areas were aggregated using ARC/INFO (Environmental Systems Research Institute, 1992) to represent the types and degrees of development in New Jersey (Figure 2). These drainage areas were also selected to maintain consistency with drainage areas previously established for the AMNET program. One advantage of using drainage basins for broad-scale comparisons is that there is an inherent hierarchical structure. The resulting five drainage areas are shown in Table 1b. The Upper Delaware River drainage area lies primarily in the Valley and Ridge physiographic province. The Lower Delaware and Atlantic Coastal River drainage areas are entirely in the Coastal Plain, and the Passaic-Hackensack-Rahway-Elizabeth and Raritan River drainage areas encompass parts of several physiographic regions (Figure 2).

ANALYTICAL APPROACH

Explanatory Variables

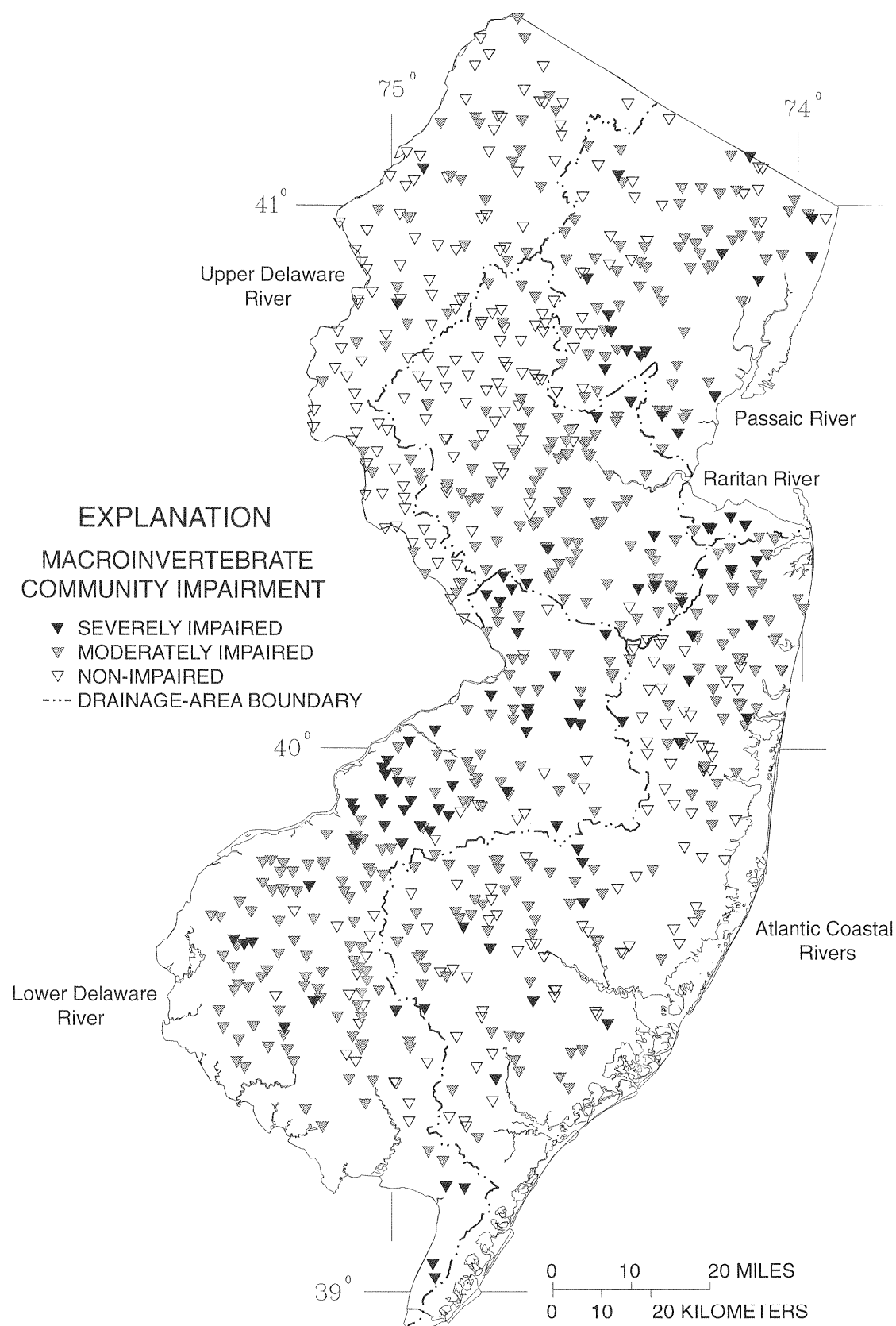Distance-weighted water-quality and basin characteristics considered in this analysis include total flow

Figure 2. Distribution of Ambient Biomonitoring Network Macroinvertebrate Sampling Sites Showing Levels of Benthic Macroinvertebrate Community Impairment in Major Drainage Basins of New Jersey.

TABLE 1a. Land Use and Population Density in Major Physiographic Regions of New Jersey [Anderson level I land-use data from Fegeas *et al.* (1983); population data from U.S. Bureau of the Census (1991)].

Land-Use Category	Percent of Physiographic Region					
	Coastal Plain (CP)	Northern Piedmont Lowlands (PL)	New Jersey/ New York Piedmont (PD)	Reading Prong (RP)	New Jersey/ New York Highlands (NH)	Valley and Ridge (VR)
Urban	18	25	78	14	16	4
Agricultural	24	48	1	33	8	45
Forest	35	23	11	51	69	46
Water	4	2	4	< 1	5	2
Wetland	16	2	4	< 1	< 1	2
Barren	2	< 1	2	< 1	1	1
Population Density (people per acre)	1.0	1.4	7.1	0.8	0.8	0.2

TABLE 1b. Land Use and Population Density in Major Drainage Areas, New Jersey [Anderson level I land-use data from Fegeas *et al.* (1983); population data from U.S. Bureau of the Census (1991)].

Land-Use Category	Percent of Drainage Area				
	Raritan River (RAR)	Passaic River (PAS)	Upper Delaware River (UDR)	Lower Delaware River (LDR)	Atlantic Coastal Rivers (ACR)
Urban	26	48	13	21	17
Agricultural	40	3	25	28	7
Forest	30	41	55	35	47
Water	1	3	3	3	9
Wetland	2	4	3	11	18
Barren	1	1	< 1	1	2
Population Density (people per acre)	1.7	4.2	0.3	0.8	0.2

from point source, total municipal effluent, biochemical oxygen demand, land use, population, and physiographic region. Total area occupied by urban, forested, and agricultural land, total population, and total area underlain by each physiographic region were obtained by using a spatial model that applies a maximum branching algorithm designed to aggregate and distance-weight attributes representing point and nonpoint sources of contamination within drainage basins (White *et al.*, 1992). This spatial model is based on an infrastructure of more than 7,200 stream reaches developed by using 1:250,000-scale digital-elevation models. Degradation of sources downstream was simulated by applying distance-weighted negative exponential decay factors to explanatory variables on the basis of distance of the source from the sampling point. Each variable was multiplied by a range of decay factors. The decay factors, numbered from 1 to 10, ranged from -1 to 0, with -1 representing maximum net loss and 0 representing no net loss (conservative substance). Because the factors were distance-weighted, sources of contamination near sampling sites were distinguished from those further upstream (Stackelberg, 1997). For example, if the applied decay factor is high (-1), sources near a sampling site are most important and distant sources contribute little to contamination at a sampling site, whereas low decay factors (0) represent sources in the entire basin above a given sampling site, indicating that distant and nearby sources may be equally

important contributors of a contaminant (O'Brien, 1997; Stackelberg, 1997). Development and application of this spatial model is discussed further in White et al. (1992) and Smith et al. (1993).

Land-use categories for the model were acquired through an integration of Landsat Thematic Mapper data for August 1985 (computerized data file available at the U.S. Geological Survey, West Trenton, New Jersey) and level I Anderson classifications of 1:250,000 land-use data digitized from high-altitude aerial photographs taken in the 1970s (Fegeas et al., 1983; Anderson et al., 1976). The minimum mapping unit for this assessment ranged from 4 to 16 hectares depending on land-use category. Six level I land-use categories described by Anderson et al. (1976) were assessed in this study. Population estimates were obtained from the 1990 Census of Population and Housing (Lanfear, 1993).

Variability Among Major Strata

Two-way analysis of variance (ANOVA) on rank-transformed impairment scores was used to evaluate differences in level of impairment among physiographic regions and major drainage areas simultaneously (SAS Institute, Inc., 1990). This is a robust, nonparametric procedure that is insensitive to outlying values in which no assumptions of normality or homogeneity of variance are made (Iman and Conover, 1983; Zar, 1984). The null hypothesis (H_0) evaluated is that the mean levels of impairment among all six physiographic regions, five major drainage areas, and their interaction are equal. Rejection of the null hypothesis indicates that at least one mean value for a physiographic region, major drainage area, or their interaction is significant. If interaction is significant, then the effect of major drainage area on mean level of impairment differs among physiographic regions; otherwise, the effect of major drainage area on mean level of impairment is identical (Helsel and Hirsch, 1992). If the null hypothesis was rejected, Tukey's honestly significant difference test (Tukey's test) was performed to determine which mean ranks differed (Zar, 1984). Null-hypothesis testing was performed at the 95 percent confidence level ($\alpha = 0.05$).

Model Development

Maximum-likelihood logistic-regression analysis of basin characteristics was used to develop equations defining the probability of relative community impairment above predetermined levels. Logistic regression

is a statistical technique that can be used to predict or model categorical response variables (e.g., benthic community impairment ratings) from one or more continuous explanatory variables (e.g., land use, physiographic region, water-quality characteristics). The result is a regression equation that describes the relations among the variables being modeled. A polytomous dependent variable based on three levels of impairment (N = nonimpaired, M = moderately impaired, and S = severely impaired) was modeled. The response variable in logistic regression is the log_e of the odds ratio, p/(1-p), where p is the probability of a continuous data value being in one of the possible categories (Helsel and Hirsch, 1992). The logistic-regression equation is $\ln [(p/1-p)] = \beta_0 + \beta X$ where β_0 is the intercept, X is the vector of k explanatory variable(s), and βX includes the slope coefficients for each explanatory variable so that $\beta X = \beta_1 X_1, \beta_2 X_2, \ldots \beta_k X_k$ (Helsel and Hirsch, 1992; Hosmer and Lemeshow, 1989). The slope coefficients are fit to the categorical response variables by the maximum-likelihood method, which optimizes the likelihood that the observed data will be estimated from a given set of slope coefficients (Helsel and Hirsch, 1992). The resulting regression parameters differ significantly from 0 at the 95 percent confidence level ($\alpha = 0.05$).

Only those variables determined to be significant at $p < 0.05$ in univariate analysis were included in the multivariate analysis. Correlation analysis indicated that variables representing the same basin characteristic at different decay rates commonly were highly collinear (Pearson correlation analysis, SAS Institute, Inc., 1990). This result is expected as levels of decay are derived from a measured value. To decrease the possibility of multicollinearity among explanatory variables, the list of variables used in the model was greatly restricted. Only those variables that produced a more significant and better fit equation in the univariate logistic-regression analysis were selected for inclusion in the multiple logistic-regression analysis. For example, if URB-1 and URB-2 were highly collinear with an $R \geq 0.90$, and URB-1 was a better fit variable in the univariate model, URB-1 would be retained and URB-2 would be removed from further analysis. Best fit multiple logistic-regression models were selected from the remaining explanatory variables that were related to levels of macroinvertebrate impairment. Explanatory variables were added to the model in order of significance ($p \leq 0.10$) by using forward selection and backward elimination procedures (SAS Institute, Inc., 1990). As variables were added, previously entered variables were removed if their p-values increased to greater than 0.15.

Three measures of goodness of fit were used to assess the relations indicated by the resulting logistic-regression equations: (1) the chi-squared statistic

(χ^2), an indication of the joint significance of the explanatory variables, which was maximized through iterative stepwise procedures in which forward selection and backward elimination of explanatory variables were used (Helsel and Hirsch, 1992); (2) the Akaike Information Criterion (AIC), which is based on the log-likelihood value adjusted for the number of explanatory variables in each equation; and (3) the rank correlation between predicted probabilities and observed responses (C), where the coefficient ranges from 0 to 1, with 1 being a perfect fit. AIC is typically used to compare different models for the same data and C is an index of rank correlation used to assess the predictive ability of the model that is based on the total number of concordant and discordant observations. In general, a high rank correlation of predicted probabilities and χ^2 statistic and low AIC indicate a well-fit model. Logistic-regression analysis is reviewed extensively in Walker and Duncan (1967), Harrell *et al.* (1980), and Hosmer and Lemeshow (1989). Applications to water quality and bed sediment are presented in Eckhardt and Stackelberg (1995), Helsel and Hirsch (1992), O'Brien (1997), and Stackelberg (1997).

RESULTS

Relation of Macroinvertebrate Community Impairment to Basin Characteristics

Rejection of the null hypothesis indicated that the levels of impairment among all six physiographic regions and five major drainage areas and their interaction were not equal (p < 0.0062, 0.0001, and 0.0002, respectively). Biological impairment of the New Jersey/New York Piedmont and Northern Piedmont Lowlands did not differ significantly from the Coastal Plain (Table 2a). These physiographic regions also had the most severely impaired sites (Table 2a, Figure 1b). Level of impairment in the Valley and Ridge did not differ significantly from that in the Reading Prong; these two physiographic regions had the fewest severely impaired sites (Table 2a). The Upper Delaware drainage area had significantly fewer impaired sites (Tukey's test) than all the other drainage areas (n = 1, Table 2b). Level of impairment in the Atlantic Coastal Rivers drainage area did not differ significantly from that in the Raritan River

TABLE 2a. Summary Statistics for Levels of Macroinvertebrate Community Impairment in New Jersey Streams and Results of Two-Way ANOVA of Physiographic Regions. (Turkey groups are reported as the letters A through D representing successively decreasing mean impairment scores. Physiographic regions that have letters in common do not differ significantly. N = number of samples; CV = coefficient of variation; * = insufficient data to compute summary statistic.)

Statistic	Physiographic Region					
	Coastal Plain (CP)	Northern Piedmont Lowlands (PL)	New Jersey/ New York Piedmont (PD)	Reading Prong (RP)	New Jersey/ New York Highlands (NH)	Valley and Ridge (VR)
Non-Impaired						
N	100	40	6	49	25	31
Median	27	27	24	30	27	30
25th-75th Percentile	24-30	24-30	24-27	27-30	24-30	27-30
Variance	6.4	6.7	6.3	2.6	7.0	4.7
CV	9.4	9.5	9.8	5.6	9.7	7.6
Moderately Impaired						
N	235	61	26	16	20	17
Median	15	15	15	13.5	16.5	18
25th-75th Percentile	12-28	12-18	12-15	9-18	11-18	15-21
Variance	15.2	15.8	8.3	22.7	18.0	28.0
CV	26.9	25.3	20.3	34.3	28.3	28.8
Severely Impaired						
N	62	11	6	1	4	1
Median	6	6	6	6	3	*
25th-75th Percentile	3-6	3-6	6-6	6-6	3-5	*
Variance	4.9	4.3	1.5	*	2.3	*
CV	49.4	44.5	22.3	*	40	*
Tukey Groups	**CD**	**BC**	**D**	**A**	**B**	**A**

TABLE 2b. Summary Statistics for Levels of Macroinvertebrate Community Impairment in New Jersey Streams and Results of Two-Way ANOVA of Major Drainage Areas. (Turkey groups are reported as the letters A through C representing successively decreasing mean impairment scores. Major drainage areas that have letters in common do not differ significantly. N = number of samples; CV = coefficient of variation; * = insufficient data to compute summary statistic.)

| | Major Drainage Areas | | | | |
Statistic	Passaic River (PAS)	Raritan River (RAR)	Lower Delaware River (LDR)	Upper Delaware River (UDR)	Atlantic Coastal Rivers (ACR)
	Non-Impaired				
N	26	54	28	86	76
Median	25.5	27	27	30	27
25th-75th Percentile	24-30	27-30	24-30	27-30	24-30
Variance	8.6	4.7	5.9	5.9	6.2
CV	10.9	7.8	8.9	8.7	9.3
	Moderately Impaired				
N	58	82	126	33	98
Median	15	15	15	15	15
25th-75th Percentile	12-18	12-18	12-18	15-21	12-18
Variance	14.5	14.5	15.5	15.1	17.9
CV	26.4	25.6	27.9	22.3	28.1
	Severely Impaired				
N	15	8	47	1	17
Median	6	6	6	*	6
25th-75th Percentile	3-6	4.5-6	3-6	*	3-6
Variance	3.6	1.9	4.6	*	5.7
CV	43.6	26.4	49.5	*	56.3
Tukey Groups	C	B	C	A	B

drainage area (Tukey's test); however, it did differ significantly from those in the Lower Delaware and the Passaic River drainage areas (Table 2b).

Forty-five of the initial 140 continuous explanatory variables assessed with univariate models showed a significant relation with community impairment. Of these, only seven variables were highly related to the level of community impairment (Table 3). Explanatory variables that best describe community impairment were the amount (in square kilometers) of land classified as urban (URB-3) and forested (FOR-3) in close proximity to sampling sites, area underlain by the Reading Prong (RP-3) and Coastal Plain (CP-3) physiographic regions, and total annual flow (in cubic feet per second) of municipal effluent (PFM-5). When all explanatory variables were included in the model (Table 4), results of the most parsimonious logistic-regression equation showed that the probability of detecting a severely impaired aquatic macroinvertebrate community was negatively related to the total area of forested and undeveloped land (km^2) and the total underlying area in the Reading Prong physiographic region, and positively related to the area of urban land aggregated upstream from a sampling site

(Table 4, Equation 3). Area of barren land located within a given drainage area was useful in explaining the level of community impairment (Table 4, Equations 1 and 2). Amount of barren land, however, was considered to be a weak variable and likely shows both a spurious correlation because of a low maximum (Table 3) and that it represents little of the overall land use in New Jersey (< 2 percent; Table 1).

To test whether underlying physiography, which dominated many of the initial models, was obscuring other potentially significant explanatory variables in the logistic-regression analysis, physiographic variables were removed and the analysis was repeated. In addition, by excluding a subsample of observations (e.g., physiography), models based on the remaining subjects were developed and used to validate the original model (Hosmer and Lemeshow, 1989). In the absence of physiographic variables, level of impairment of aquatic communities was most strongly related to land use and total flow of municipal effluent (Table 5). Total flow of municipal effluent was positively related to the level of community impairment (Table 5, Equation 1), indicating that drainage areas with high flows of municipal effluent are likely to

TABLE 3. Statistics for Coded Response Variables and Continuous Explanatory Variables
(km^2, square kilometers; ft^3/s, cubic feet per second; EPT, Ephemeroptera, Plecoptera,
Trichoptera; N, number of samples; SD, standard deviation; >, greater than).

Polytomous Response Variables				
Level of Impairment and Range of Scores	Variable Code and Description	N	Mean	SD
Non-Impaired Range (24-30)	1 – Benthic macroinvertebrate community is comparable (> 79 percent) to those in other undisturbed streams and is characterized by high taxa richness, high equitability, and many intolerant individuals.	251	27.4	2.5
Moderately Impaired Range (9-21)	2 – Reduced macroinvertebrate richness and EPT abundance, low equitability, and an absence of intolerant taxa.	375	14.8	4.0
Severely Impaired Range (0-6)	3 – Community is dominated by a few highly abundant species and tolerant taxa typically are the only individuals present.	85	4.5	2.2

Continuous Explanatory Variables				
Variable Name	Description, Unit of Measurement, and Source of Data	Minimum	Median	Maximum
FOR-3	Area of forested and undeveloped land (km^2) aggregated upstream with a decay factor of -0.1 (Fegeas et al., 1983)	0	5.0	52.8
URB-3	Area of Landsat Thematic Mapper data for August 1985 classified as urban land (km^2) aggregated upstream with a decay factor of -0.1.	0	3.6	100.4
CP-3	Area underlain by the Coastal Plain physiographic region (km^2) with a decay factor of -0.1.	0	6.3	110.6
RP-3	Area underlain by the Reading Prong physiographic region (km^2) with a decay factor of -0.1.	0	6.9	50.8
FOR-7	Area of forested and undeveloped land (km^2) aggregated upstream with a decay factor of -0.007 (Fegeas et al., 1983).	0	7.4	555.9
BAR-5	Area of barren land (km^2) aggregated upstream with a decay factor of -0.3 (Fegeas et al., 1983).	0	0.1	11.5
PFM-5	Total flow of municipal effluent (ft^3/s) with a decay factor of -0.3 (Robinson et al., 1995).	0	0	36.6

have a severely impaired macroinvertebrate community. After several model iterations, the single best predictor variable was retained, indicating that the probability of detecting a severely impaired aquatic macroinvertebrate community was negatively related to area of forested land aggregated upstream (Table 5, Equation 3). This result is consistent with the results of the previous logistic-regression analyses in which all variables were retained (Table 4). Thus, even in the absence of physiographic effects, the amount of forested land is strongly and inversely related to severe community impairment.

DISCUSSION

These results clearly illustrate the strong association of upstream land use and water-quality characteristics with macroinvertebrate community condition in lotic ecosystems. Generally, logistic-regression analysis showed that severe community impairment was most significantly and positively related to amount of urban land and total flow of municipal effluent, and most significantly and negatively related to amount of forested land.

TABLE 4. Logistic-Regression Equations and Associated Goodness-of-Fit Statistics for Models Where All Explanatory Variables Were Retained. (Variable names are described in Table 3; χ^2 = chi-squared statistic; C = rank correlation of predicted probabilities and observed responses; AIC = Akaike Information Criterion; p-values for individual variables are based on Wald's chi-squared statistic, which is the square of the parameter estimate divided by its standard error estimate with one degree of freedom.)

Equation Number	Equation			Goodness-Of-Fit Statistic		
	Explanatory Variable	Coefficient β_i	p-Value (Wald's)	χ^2 (p-value)	C	AIC
1	URB-3	0.066	0.0001	131.8	0.729	1245.7
	FOR-3	-0.060	0.0001	(0.0001)		
	CP-3	0.023	0.0001			
	BAR-5	-0.445	0.0003			
	RP-3	-0.060	0.0002			
	INTERCEPT	-2.198	0.0001			
2	URB-3	0.064	0.0001	114.5	0.719	1261.1
	FOR-3	-0.076	0.0001	(0.0001)		
	CP-3	0.032	0.0001			
	BAR-5	-0.414	0.0005			
	INTERCEPT	-2.248	0.0001			
3	URB-3	0.051	0.0001	101.9	0.714	1271.6
	FOR-3	-0.056	0.0001	(0.0001)		
	RP-3	-0.075	0.0001			
	INTERCEPT	-1.930	0.0001			
4	URB-3	0.049	0.0001	70.5	0.686	1301.1
	FOR-3	-0.066	0.0001	(0.0001)		
	INTERCEPT	-1.922	0.0001			
5	FOR-3	-0.043	0.0001	30.8	0.626	1338.7
	INTERCEPT	-1.678	0.0001	(0.0001)		

TABLE 5. Logistic-Regression Equations and Associated Goodness-of-Fit Statistics for Models Where Physiographic Region Variables Were Removed. (Variable names are described in Table 3; χ^2 = chi-squared statistic; C = rank correlation of predicted probabilities and observed responses; AIC = Akaike Information Criterion; p-values for individual variables are based on Wald's chi-squared statistic, which is the square of the parameter estimate divided by its standard error estimate with one degree of freedom.)

Equation Number	Equation			Goodness-Of-Fit Statistic		
	Explanatory Variable	Coefficient β_i	p-Value (Wald's)	χ^2 (p-value)	C	AIC
1	URB-3	0.049	0.0001	101.9	0.684	1292.7
	FOR-7	-0.017	0.0001	(0.0001)		
	PFM-5	0.228	0.0001			
	INTERCEPT	-1.930	0.0001			
2	URB-3	0.049	0.0001	70.5	0.686	1301.1
	FOR-3	-0.066	0.0001	(0.0001)		
	INTERCEPT	-1.922	0.0001			
3	FOR-3	-0.043	0.0001	30.8	0.626	1338.7
	INTERCEPT	-1.678	0.0001	(0.0001)		

A corresponding logistic-regression analysis of organic contaminants in bed sediments in New Jersey showed the presence of organic contaminants to be strongly related to basin population and residential land use (Stackelberg, 1997). Similarly, O'Brien (1997) found that the presence of certain trace elements was related to basin population, agricultural land use, and underlying geology. For most variables

in these models, stronger correlations and better fit equations were derived by using variables within close proximity to the sampling site (high decay factor). In the current study, one exception was the decay factor associated with FOR-7, which was negatively related to a severely impaired aquatic community (Table 5, Equation 1). This value represents little decay from the source, indicating that the total amount of forested land is an important determinant of the level of community impairment regardless of its location within the basin.

These findings are consistent with those of earlier studies by Omernik et al. (1981), Smart et al. (1981), and Osborne and Wiley (1988), all of whom found the amount of forested land to be positively related to favorable water quality. More recently, Richards and Host (1994) and Richards et al. (1996) found a strong correlation between amount of forested land and benthic invertebrate community structure. A similar investigation by Roth et al. (1996) indicated that the amount of forested land in a basin was directly related to Index of Biotic Integrity (IBI) scores, a measure of fish-community condition.

Significant relations with urbanization are particularly prevalent in most of the best fit models assessed (Tables 4 and 5). Many studies have shown that extensive urban development and runoff can degrade lotic aquatic communities. Benke et al. (1981), Pitt and Bozeman (1983), and Duda et al. (1982) found a significant inverse relation between taxa richness and degree of urbanization in a watershed. In a Virginia stream, urbanization was associated with an increase in tolerant taxa and a decrease in macroinvertebrate diversity (Jones and Clark, 1987). Garie and McIntosh (1986) found that benthic invertebrate richness, population density, and a shift in community composition was directly related to increasing urbanization in a Trenton, New Jersey, stream. Similarly, Klein (1979) found a direct negative relation between degree of urbanization and the diversity of fish populations. In a study of 134 Wisconsin streams, Wang et al. (1997) found that urban land use is strongly associated with poor biotic integrity and that a significant positive correlation existed between IBI scores and habitat quality. Clearly, increasing urban and decreasing forest land use greatly affects the integrity of aquatic communities. These relations illustrate the ecological value of watershed management. Cooperative efforts to restore damaged waterways or protect forested areas in watersheds from further urbanization should be paramount.

Total flow of municipal effluent was found to be useful in explaining the level of community impairment when physiographic variables were removed (Table 5, Equation 1). This result is similar to that of a study of nutrients in streamwater, in which total phosphorus concentrations were related to total flow from municipal point sources in close proximity to the sampling location (Smith et al., 1993). In a study of upland streams, Wright et al. (1995) found that benthic communities at sites that received sewage effluent showed a marked difference in taxonomic richness from reference communities at sites that did not. Although links between sewage effluent and macroinvertebrate community impairment have been known since the early 1900s, the strong relation found in urban New Jersey streams further substantiates this association.

The Coastal Plain and the New Jersey/New York Piedmont did not differ significantly (Tukey's test) and had the highest probability of exhibiting an impaired macroinvertebrate community (Table 2). This result is contrary to what would typically be expected for some streams located in the Coastal Plain of New Jersey. However, naturally depauperate communities in New Jersey Pinelands streams exhibiting low bioassessment scores may account for our failure to reject the null hypothesis for the Coastal Plain and New Jersey/New York Piedmont. This suggests that metric criteria for reference streams in the coastal region of New Jersey may need to be reevaluated. In addition, the Coastal Plain was not divided into inner and outer sections (see Figure 1b) for this analysis. Thus, the highly urban corridor just outside Philadelphia, Pennsylvania, which comprises much of the Inner Coastal Plain, may be influencing this result by skewing these data. Analysis of major drainage area indicates that levels of impairment in the Atlantic Coastal Rivers drainage area, which comprises most of the Outer Coastal Plain, do differ significantly from those in the Lower Delaware River drainage area, which comprises much of the Inner Coastal Plain. Significant interaction ($p < 0.0002$) indicates that the effect of major drainage area on mean level of impairment does differ among physiographic regions. Additional analysis on a smaller scale may statistically differentiate the Outer Coastal Plain, which contains New Jersey's Pine Barrens and large tracts of undeveloped and forested land, from the more urbanized New Jersey/New York Piedmont.

The Reading Prong and Valley and Ridge physiographic regions have the lowest percentage of urban land use and the lowest human population density, and are least likely to exhibit a severely impaired macroinvertebrate community (Tables 1 and 2a). This finding is consistent with that found for the major basins because a large proportion of the area of these two physiographic regions is in the Upper Delaware River drainage area (Figure 2), which is significantly different (Tukey's test) from the other four major drainage areas, is least likely to exhibit a severely

impaired community, and has the highest percentage of forest land use (Tables 1 and 2b). The urbanized and highly populated Passaic River and Lower Delaware River drainage areas do not differ significantly from each other and have a higher probability of exhibiting a severely impaired macroinvertebrate community than do the other drainage areas (Table 2b).

Currently, many of the mechanisms associated with the degradation of aquatic communities are understood. Increasing urbanization (Jones and Clark, 1987), urban runoff (Garie and McIntosh, 1986), increased suspended-sediment loads (Culp et al., 1986), habitat quality (Wang et al., 1997), and sewage effluent (Wright et al., 1995) have been shown to affect the hydrology, geomorphology, and water quality of lotic systems. This approach of integrating multimetric and multivariate data proved to be a relatively robust predictor of differences in level of community impairment. A similar approach can be applied to fish communities by using IBI as well as other multimetric assessments using benthic invertebrates (e.g., B-IBI, Kerans and Karr, 1994) when basin characteristics and water-quality information also are available.

This study describes the statistical relations between the level of benthic community impairment and water-quality and land-use characteristics at the drainage-area and physiographic-region scale. Even at this relatively coarse scale, specific variables emerged as good predictors of impairment. Amount of forested land proved to be the best predictor of an unimpaired benthic community, whereas amount of urban land was the best indicator of a severely impaired benthic community. Ultimately a more comprehensive understanding of the structure of benthic communities in New Jersey streams will include additional analysis integrating surrounding landscape features at multiple spatial scales (stream reach, stream segment, and basin) and a more detailed water-quality assessment.

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